

## **Style of surface deformation produced by the 1999 Chi-Chi (Taiwan) earthquake and effects on the built environment**

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### **INVESTIGATIONS UNDERTAKEN**

This research is evaluating the effects of ground deformation from the 1999 Chi-Chi earthquake on several buildings along the fault rupture. Because the earthquake produced surface rupture through densely populated areas, it provides an unprecedented opportunity to advance the understanding of the effects of surface fault rupture on engineered systems. The observations of damage resulting from these occurrences have a great potential to redefine U.S. practice in terms of zoning policies and surface fault-rupture mitigation measures.

Our objectives in this research are to:

- (1) Document the style of surface deformation from the Chi-Chi earthquake;
- (2) Establish relationships or patterns between the style of geologic deformation, geotechnical conditions, and effects on the built environment
- (3) Develop geologic and geotechnical information useful for developing appropriate zoning schemes and improving earthquake-resistant building designs for areas containing active reverse faults with surface-rupture potential

This research represents an integrated approach toward evaluating the effects of fault-related geologic deformation on buildings and other engineered facilities by combining investigative approaches from the fields of geotechnical engineering and engineering geology. We are conducting a series of integrated geologic and geotechnical activities at several representative sites along the rupture. At each site, these activities include documentation of geologic conditions via detailed surveying and mapping, description of geotechnical conditions, and assessment of building damage. We are synthesizing these data sets to develop information that is critical for developing effective fault-rupture mitigation strategies. The results from this effort will be directly applicable to engineering analyses designed to improve hazard mitigation and develop better building designs. In addition, we anticipate that the results of this study will provide guidance for developing or revising fault-rupture zonation policies for metropolitan areas in the United States that are exposed to surface rupture along active reverse faults.

## RESULTS

Our efforts during this investigation have focused on collecting geologic and geotechnical data at four sites along the west-vergent Chelungpu thrust fault rupture: (1) the KuangFu Middle School in WuFeng, (2) near the Suncue Factory in WuFeng, (3) at the ChungShin Provincial Hospital in Tsaotun, and (4) at the Municipal Water Tower near Tsaotun.

At the KuangFu Middle School, we completed detailed topographic surveying to better delineate the pattern of surface faulting and ground deformation throughout the school campus. The ground deformation at this site was still preserved at the time of our survey, and remains mostly intact today because of the development of the island's Earthquake Museum. Our survey area includes several school buildings, some of which were severely damaged and some of which remain standing. Directly southeast of the site, a single, well-defined fault rupture crosses the school's track and field (see Kelson et al., 2001). Our recent surveying shows that this rupture splays into three distinct strands in the vicinity of the school buildings. The westernmost strand deforms the southern end of one of the school buildings, which was severely damaged but did not collapse. On the western side of this building, this strand progressively increases in vertical displacement. The central strand begins on the western side of the building and extends northwesterly across the site, until it dies out directly north of the campus boundary. The easternmost strand skirts along the eastern margin of this building, and decreases in amount of displacement to the north until it too dies out directly north of the campus boundary. In the campus area containing the three fault strands, the total net vertical displacement from faulting and folding (about 3 m) appears to be consistent across the site, with the pattern suggesting a transfer of shortening progressively from the eastern strand to the westward strand. We currently are analyzing the possibility that the school building interacted with the shallow part of the fault rupture to influence this deformational pattern.

As part of this analysis, we also collected existing geotechnical borehole data and conducted shallow drilling to characterize the soil/alluvium and to define the depth to bedrock beneath the site. These data suggest that the total displacement on the top of bedrock is substantially more than the 3 m displacement produced by the 1999 earthquake. Importantly, the displacement in the bedrock surface appears to not coincide with the location of the 1999 displacements. We are analyzing this information to evaluate whether or not the 1999 rupture location differs substantially from the locations of previous rupture. In addition, we conducted a detailed manometer survey of the floor of the building, and collected structural information on the building and its basement to assess its pre-earthquake structural integrity. Using this information, we believe that we will be able to model the effects of the surface rupture on the building, and infer the mode of interaction between the thrust shallow soil and the building.

At the Suncue Sheet Metal Factory, we collected additional subsurface information to supplement our previous topographic surveying of the site, which suggest that the factory building strongly influenced the pattern of the fault rupture trace (Kelson et al., 2001). Our new data include information from two air-rotary boreholes, which show the depth to bedrock is about 5 m beneath the hanging wall and more than 18 m beneath the footwall. These data suggest recurrent movement on the fault through the site, which is now occupied by the factory building. The soil materials above the bedrock are primarily cobble-gravel deposits. We also obtained structural information on the building, which we will integrate with the characteristics of the near-surface soil and detailed surveying to evaluate the interaction between the building and uplifted soil.

At the ChungShin Provincial Hospital, we completed a detailed planimetric map of a hospital wing that has since been razed as a result of earthquake demolition efforts. This mapping shows that the building was strongly affected by ground deformation on the hanging wall adjacent to the primary fault rupture. The building floor was strongly folded, with evidence of anticlinal deformation traversing several individual rooms. Our manometer surveys of several rooms

shows floor tilts of as much as 10°. We are analyzing whether or not this building damage is related solely to secondary tectonic deformation on the hanging wall, or is related to possible landsliding of material into the eastern wall of the building.

At the Tsaotun Municipal Water Tower, we conducted detailed topographic surveying and geologic mapping of the fault rupture as it intersects a 12-m-wide, 26-m-high concrete water tower. To the south of the tower, the fault rupture is expressed as a single, 2-m-high west-facing fault scarp that projects directly toward the water tower. At the tower, the scarp wraps around the eastern side of the tower, where anticlinal deformation of the hanging wall is intense. A drainage ditch along the eastern margin of the tower is completely closed and deformation adjacent to the tower. To the north of the tower, the scarp bifurcates into two or three scarps within a zone of distributed folding and faulting. In this area, the overall trend of the deformational zone is similar to that south of the tower, and the adjacent drainage ditch is relatively undeformed. It appears that the presence of the tower affected the distribution of deformation at this site. In addition, we collected structural information about the tower itself from the local water company. During the 1999 earthquake, the tower was empty of water, and it shows no evidence of structural damage as a result of its interaction with the fault rupture. The tower can be modeled as a tall, isolated concrete cylinder. Using these data, we will integrate the geologic and structural information to help interpret the pattern of fault rupture and the interaction between the fault and the tower.

## **NON-TECHNICAL SUMMARY**

This research provides geologic data to help address how the ground along a fault rupture deforms and affects nearby buildings. We are documenting the pattern of ground deformation at four sites along the Chelungpu fault that experienced severe to moderate faulting as a result of the M7.6 Chi-Chi earthquake on September 21, 1999. We are then comparing the characteristics of this deformation with the style and amount of damage that occurred to several buildings at these sites. Initial results show that some positions along the fault rupture are extremely hazardous but, surprisingly, other positions may not result in severe building damage. Our studies are continuing to define why some locales and some buildings are more (or less) susceptible to severe damage from surface fault rupture.

## **REPORTS PUBLISHED**

This research has contributed in part to the following formal publications and abstracts:

- Kelson, K.I., Kang, K.-H., Page, W.D., Lee, C.-T., and Cluff, L.S., 2001, Representative styles of deformation along the Chelungpu fault from the 1999 Chi-Chi (Taiwan) earthquake: Geomorphic characteristics and responses of man-made structures: Bulletin of the Seismological Society of America, Special Volume on the 1999 Chi-Chi (Taiwan) Earthquake [in press].
- Kelson, K.I. (coordinator) and 13 other contributors, 2001, Fault-related surface deformation: *in* Uzarski, J., and Arnold, C. (eds.), Chi-Chi, Taiwan, Earthquake of September 21, 1999 Reconnaissance Report: *Spectra*, Earthquake Engineering Research Institute, Supplement A to v. 17, p. 19-36.
- Kelson, K.I., Lee, C.-T., Kang, K.-H., and Page, W.D., 2000a, Styles of surface deformation along the Chelungpu fault resulting from the 1999 Chi-Chi earthquake [abs.]: Symposium on Mitigation of the Risk of Surface Faulting, sponsored by the Taiwan National Science Council, National Central University, and Geophysical Society of China; ChungLi, Taiwan, April 6-7, 2000.

Kelson, K.I., Kieffer, S., Sitar, N., Wright, R., Wells, D., and Perkins, W., 2000b,  
Fault-related deformation resulting from the Chi-Chi (Taiwan) earthquake:  
Preliminary conclusions of the NSF-PEER reconnaissance team [abs.],  
Seismological Society of America Annual Meeting, San Diego.

#### **DATA AVAILABILITY**

Additional detailed information on the investigation is available from the Principal Investigator first listed above. This information includes detailed site maps and logs of shallow borings.